carbon, nitrogen, oxygen, and silicon about the same abundance. The silicon has twice the energy per ray of the mean of carbon, nitrogen, and oxygen, so that it might be expected to carry about 40 percent of the energy of the four bands. That is not very much more than what it does carry if one attributes to it all the increase in electroscope readings between Bangalore and Peshawar (blocks 5 and 6 Fig. 8). Again, if the band between San Antonio and Oklahoma City (block 3) is taken as the contribution of carbon rays it comes out reasonably close to half of what is left of the energy carried by carbon, nitrogen, oxygen, and silicon after the carbon and silicon have been deducted. Also, if the helium band is responsible for all the new rays added above carbon its energy is a little more than the mean of the carbon, nitrogen, and oxygen bands. It ought to carry roughly twice as much energy as any of them, since each ray has about one-fourth as much energy as the mean of these three, but Bowen gives it ten times their abundance. He probably would not regard his estimates as sufficiently quantitative to make the discrepancy serious.

In conclusion, it may properly be asserted that there is already a reasonable amount of evidence for the actual existence of the five predicted bands and the four predicted plateaus, and the relative energies brought in by the five bands are in every case at least of the predicted order of magnitude.

This comparison of prediction and experiment has been made possible largely through the generous support of the investigation by the Carnegie Corporation of New York and the Carnegie Institution of Washington. The success of the work in India was made possible by the extraordinarily generous and complete cooperation of the British Indian Meteorological Service.

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Results of a High Altitude Cosmic-Ray Survey Near the Magnetic Equator

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Electroscope and Geiger counter observations have been taken with free balloons at geomagnetic latitudes of 3°, 17°, and 25°N. The most important results are as follows: (1) The Geiger counter technique with a single counter will give results very close to those obtained with the electroscope and of comparable accuracy. (2) Vertical coincidence measurements give rise to markedly different values for the relative amounts of incident energy at various latitudes, as compared with the electroscope or single counter data. (3) Within the experimental error, no difference was obtained between the vertical coincidence curves at 3° and 17°, and thus no new energy lies in the primary energy spectrum between the limits of 17 and 15 Bev. (4) This is direct evidence for a banded structure in the primary cosmic-ray spectrum. (5) Flights made with triple and quadruple coincidences, and also with counters arranged to record showers, showed that showers do not significantly affect the vertical coincidence measurements.

INTRODUCTION

In order to measure the primary energy distribution of the cosmic radiation, observations of the incident energy at the top of the atmosphere in different parts of the earth are necessary. These data, in conjunction with the analysis of the effect of the magnetic field of the earth upon incoming charged particles, can yield the required information. During the last few years Millikan and Neher have taken such data with self-recording electroscopes in several different magnetic latitudes. Although this technique is entirely satisfactory in most respects, there are two limitations inherent in the method. These are: (1) the electroscopes can be released only in such places and at such times that the chance of

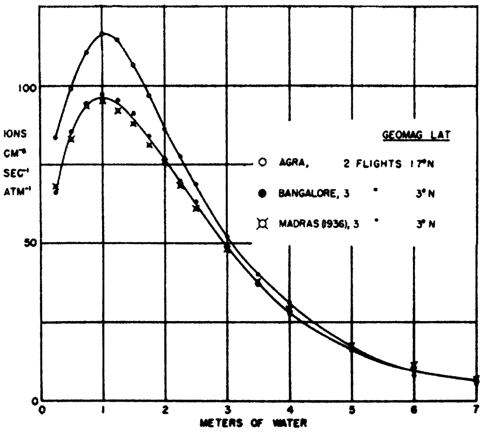

FIG. 1. Average data for electroscope flights at magnetic latitudes 17°, and 3° north.

recovery is reasonably good, and (2) the electroscope gives the integrated intensity over the whole dome of the sky and thus cannot be used for any "fine structure" analysis of the incident energies.

A procedure which surmounts these difficulties at the expense of considerably increased experimental complication is the use of Geiger counters to record the radiation. Such a record can be readily adapted to radio transmission to the ground. An apparatus suitable for this is described in a paper which will appear in *The Review of Scientific Instruments*. By arranging two or more counters as a cosmic-ray telescope, only the radiation from a selected part of the sky is recorded, and thus the energies recorded are delimited with considerably greater accuracy than in the case of the electroscope.

This paper is a report of high altitude free balloon observations with both electroscope and counter techniques in latitudes near the magnetic equator. The observations were made in India by R. A. Millikan and the authors during the period from November, 1939 to February, 1940.

ELECTROSCOPE FLIGHTS

The electroscopes used for these flights were similar to those used previously, and have been described elsewhere.[1] Flights were made at two latitudes—Bangalore, magnetic latitude 3° north; and Agra, magnetic latitude 17° north. Three good records were obtained at Bangalore and two at Agra. In 1936, one of us (H. V. N.) made a series of flights in Madras in almost the same magnetic latitude as Bangalore. For comparison the average values of these flights are shown together with the averages for the new flights in Fig. 1. The curves give the intensity of the radiation as a function of the barometric pressure reduced to meters of water. Comparing the Bangalore curve with the Madras curve made three years earlier, it is apparent that no appreciable change in the radiation at the magnetic equator has taken place in that period. The two curves are within about 2 percent of each other at all points. The two groups of flights were also made at different seasons—October, 1936 and January, 1940—and the close fit of the curves shows that there is no equatorial seasonal effect, at least for these particular seasons. Hence the comparison made below of the data taken at Agra with that at Bangalore two months later, will not be complicated by seasonal effects.

The Agra curve shows a greater intensity than that at Bangalore, the integrated area under the curve being some 8 percent greater. As previously shown,[2] this area is proportional to the incident energy per square centimeter per second at the top of the atmosphere, and thus some 8 percent more of the primary energy can penetrate the earth's magnetic field at Agra than at Bangalore, which, for all practical purposes can be regarded as on the magnetic equator. In passing from the equator to the latitude of Agra the energy necessary for vertical incidence decreases[3] from 17 to about 15 Bev. However, the minimum energy necessary to reach the earth at very oblique incidence decreases from about 11 to 9 Bev. Clearly then, the 8 percent increase in incident energy at Agra can be caused by new incoming particles which might have any energy value between 9 and 17 Bev.

SINGLE COUNTER FLIGHTS

The Geiger counters used were of the "fast" type, having a mixture of argon and organic

[1] Millikan, Neher, and Haynes, Phys. Rev. **50**, 992 (1936).

[2] Bowen, Millikan, and Neher, Phys. Rev. **53**, 855 (1938)

[3] From curves appearing in Lemaitre and Vallarta Phys. Rev. **49**, 719 (1936), and **50**, 503 (1936). We obtained the values 17.0, 15.4, and 12.4×10^9 ev for the energies of vertically incoming rays at 0°, 17.3° (Agra) and 25° (Peshawar).

vapor as the gas. The cylinders were 15 cm long, the diameters varied somewhat, but on the average were about 3.5 cm. The gas pressure was about 10 cm of mercury and the operating voltage about 1200 to 1300 volts. The counters were tested by exposure to high temperatures and high counting rates, and were required to have a reasonably good plateau several hundred volts long. By using these "fast" counters in the appropriate circuits, no correction for a decrease in counter efficiency at high counting rates is necessary.

In order to calibrate the counters used on the single counter flights they were exposed to the radiation from a source of Th C″ filtered through about 2 cm of lead. This gave a counting rate somewhat larger than that reached during the flights in the equatorial region. The background counting rate inside the lead shield used above was also measured. Thus the net counting rate due to a constant radiation was found for each counter, and accordingly all counting rates observed during actual flights could be reduced to the rate of a standard counter. Upon our return from India the calibration of several of these counters was repeated and no changes greater than 5 percent were found. As an approximate check on the relationship between the ionization and the counting rate of the standard counter, the ionization corresponding to the Th C″ source used above was measured with one of the balloon electroscopes placed in the lead shield in the same location as the counters. This, of course, would not be expected to give an accurate reduction of the counts observed on the flights because of the very different geometry in the two cases. Actually it was found that the flight counting rates had to be lowered by a further 19 percent to give good agreement with the ionization measured in the electroscope flights.

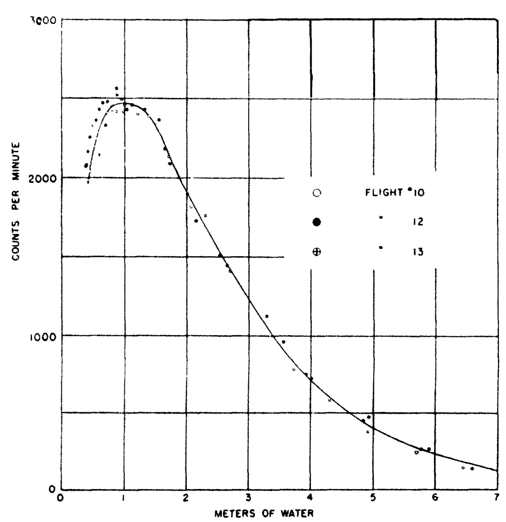

FIG. 2. Data from single counter flights at magnetic latitude (Agra) 17° north. Corrected to standard counter and for background counting rate.

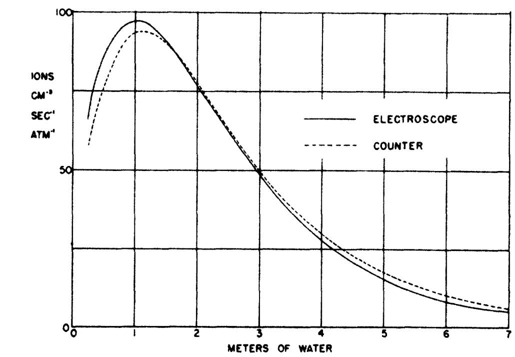

FIG. 3. Comparison of electroscope and single counter flights at the magnetic equator. The counter curve is fitted to the electroscope curve to give approximately the same area under each curve.

For these counter flights, the single counter was mounted on top of the amplifier unit with its axis at an angle of 45° with the horizontal. This was done in order to give a somewhat more uniform response to the total radiation than would be obtained with the counter horizontal. Flights were made in three locations: Bangalore and Agra, and in addition, Peshawar in magnetic latitude 25° north. The data obtained are plotted as a function of barometric pressure by taking four-minute averages of the counting rate and pressure. The consistency between the various flights in each latitude is quite good. As an example the data from the Agra flights are shown in Fig. 2. The agreement between the electroscope and the counter data is very satisfactory provided one makes the 19 percent additional geometrical correction mentioned above. Figure 3 shows this comparison for Bangalore. It will be noted that the two curves fit very well up to an altitude of about 1.5 meters of water. Above this the counter curve falls below the other. This is to be expected, because at high

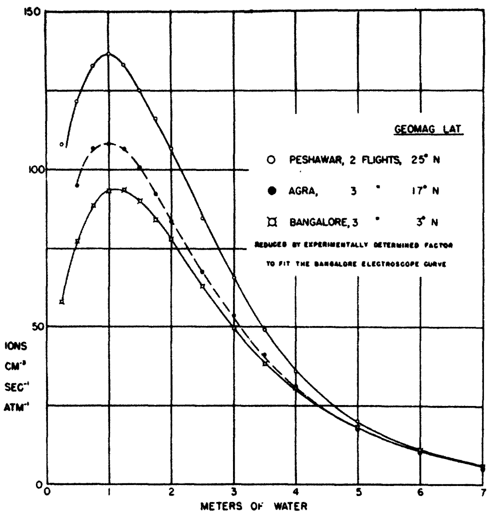

FIG. 4. Data from single counter flights. If the area under the Bangalore curve is taken as 100, then the areas under the other curves are 111 and 136, respectively.

altitudes groups of particles must become increasingly prevalent, and these register but once in the counter whereas they give their true value in the electroscope.

The averages of all the single counter flights are shown in Fig. 4, plotted in terms of ionization calculated as above. If the area under the Bangalore curve is taken as 100, then the other areas are 111 and 136, respectively. There is thus a marked increase in the primary intensity between the two latitudes of 17° and 25° north. The energies required for vertical incidence at these latitudes are 15 and 12.5 Bev, respectively.

VERTICAL COINCIDENCE FLIGHTS

In addition to the amplifier units that could be used for single counter flights, other units were built to use for double, triple, or quadruple coincidence observations. Vertical coincidence measurements, as stated above, have the significant advantage over single counter or electroscope measurements that they narrow down the band of primary energies that are recorded. Thus, in principle, these flights should give a much more satisfactory analysis of the primary energy distribution.

Double coincidence measurements were taken at the three locations of Bangalore, Agra, and Peshawar. The counter sets used for these flights consisted of two pairs of counters mounted with the members of each pair separated about 7.5 cm, and the vertical distance between the pairs about 14.0 cm. Hence the solid angle over which at least half the counter area was effective, measured about 45×25 degrees. The counting rates of the different sets were reduced to the rate of a standard set by taking calibration runs immediately before the flights. This was done by comparing the counting rate with that of the standard set when placed in some fixed position at the ground station. At least 15,000 counts were used for these calibrations. Some of the sets used were also recalibrated in Pasadena after our return. A further check on the calibration was obtained by calculation from the geometry of the sets which varied somewhat due to variations in counter diameter and spacing. The results of the flights were then weighed with due regard to the consistency of these three calibrations.

The results of the vertical coincidence flights are shown in Figs. 5 and 6. Again four-minute averages are used to obtain the curves. Figure 5 shows the actual data obtained on a flight at Peshawar after reduction to the standard counter set. The averages of all the flights are shown in Fig. 6. This includes three flights at Peshawar, four at Agra, and six at Bangalore. The comparison between the data at the different latitudes gives the following result. If the area under the Bangalore curve is taken as 100, then that under the Agra curve is also 100, and that under the Peshawar curve is 121.

By a similar analysis to that of the electroscope and single counter curves, it is possible to show that the area under the vertical coincidence curves is proportional to the vertical energy incident at the top of the atmosphere, provided that one makes the following assumptions:—(1) secondaries produced along the path of the incident particle do not diverge appreciably from the direction of the primary; (2) the passage of several secondaries through the counters simultaneously is a relatively rare event; (3) the contribution to the observed counting rate of showers arising from primaries making a large angle with the vertical can be neglected. Assumption (1) is justified from theoretical considerations,[4] assumption (2) is verified experi-

[4] T. H. Johnson, Phys. Rev. 56, 226 (1939).

mentally by the close agreement between the single counter and the electroscope curves, and (3) is verified experimentally by the results discussed in the next section. Hence the area under the vertical counter curves can be taken as giving a measure of the incident energy per square cm, per second, per unit solid angle at the vertical, at the top of the atmosphere. A numerical value can be obtained for this energy by using the known counting rate of the standard set at sea level in high latitudes where the number of particles per square cm, per second, per unit solid angle is known,[5] and an average value of the ionization per cm of path of the cosmic-ray particles in the air. Using a value of 80 ion pairs per cm,[6] one finds the vertical energy incident at the magnetic equator to be 2.2×10^8 ev/sq. cm/sec./unit solid angle.

The agreement between the Bangalore and Agar curves is considered to be well established within the limits of error of the data. On a statistical basis alone, the probable error of each point on the average curves is less than 1 percent in the region of the maximum. The internal consistency of the data is not this good, but indicates an error of about 3 percent in each curve at the maximum. Since the single counter and electroscope flights were made at the same time as these flights, the results show clearly that a real and marked difference exists between the change in the vertical radiation and the change in the integrated radiation. This difference must be ascribed to low energy particles which fail to reach the vertical counters at the higher latitude because of the gradual opening of the cones of permitted directions. In view of the complicated nature of the expressions for the effect of the earth's magnetic field on the radiation, it is clear that the vertical coincidence data are more satisfactory for the determination of the primary energy spectrum than the single counter or electroscope data. The limiting energies for vertical incidence at the three latitudes at which observations were made, are approximately as follows: —Bangalore, 17 Bev, Agra, 15 Bev, and Peshawar, 12.5 Bev. Hence, our experimental result leads to the conclusion that there is no new energy lying in the primary energy range from 17 to 15 Bev but that there is a new energy band that gets in between 15 and 12.5.

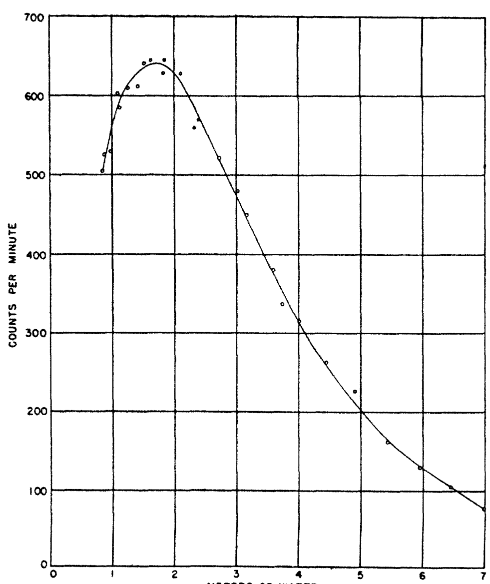

FIG. 5. Example of the data obtained from one vertical coincidence flight at Peshawar (doubles).

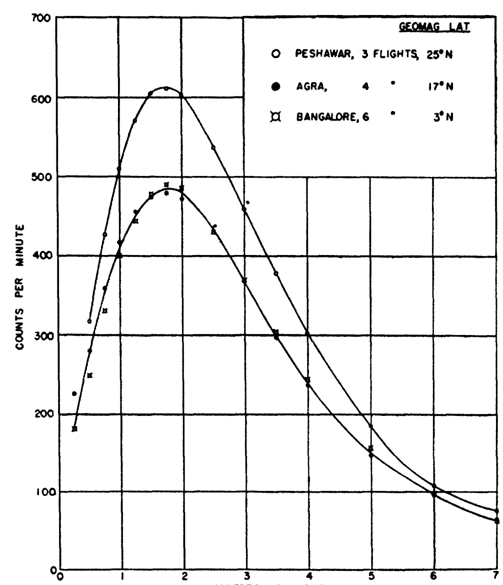

FIG. 6. Summary of vertical counter data. No detectable increase in intensity is observed between latitudes 3° and 17°, but there is a 21 percent increase in going from latitude 17° to 25°.

[5] J. C. Street and R. H. Woodward, Phys. Rev. 46, 1029 (1934).
[6] R. B. Brode, Rev. Mod. Phys. 11, 222 (1939).

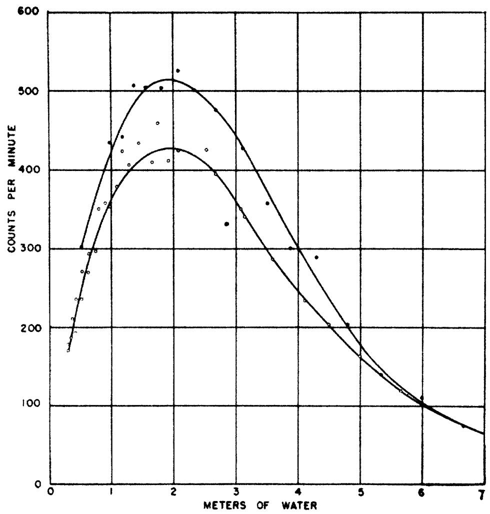

FIG. 7. Two triple vertical coincidence flights. Solid circles, Peshawar; open circles, Bangalore. The difference shown at these two latitudes is about the same as was found in the case of double coincidences; however, the maxima of the curves are about 15 percent lower than the corresponding double coincidence curves.

AIR SHOWERS

The contribution of air showers to the vertical coincidence counting rate was estimated by the following experiments. At Bangalore and at Peshawar triple coincidence flights were made in addition to the double coincidence flights. In each case the observed counting rates were lower for the triple coincidences (Fig. 7). At the maxima of the curves the difference is about 15 percent. However, the areas under the curves obtained for the two cases are not very different. The difference between the double and triple coincidences cán be caused only by showers since experiments showed that the accidental counting rate, even in the case of the double coincidences, was only about 1.5 percent of the real coincidences at the highest counting rates. The triple coincidences are lower because of the decreased proabability that a shower will operate three counters. These flights accordingly show that the effect of showers is small, and that we are justified in using the double coincidence counting rate as a measure of the vertical intensity. Because of the greater accuracy of these double flights, our conclusions are based upon them.

An interesting check on the above results is afforded by a quadruple coincidence flight made at Agra (Fig. 8). Within the quite large experimental error in this particular flight in which the counting-rate is of course very much reduced, we obtained the same result as the triple coincidence flight at Bangalore.

The difference curves between the double and triple coincidence flights rise rapidly to a maximum at about 1.5 meters water equivalent depth below the top of the atmosphere. They then fall to zero at a depth of about 4.0 meters. This behavior is similar to that observed in a flight made at Bangalore with three pairs of counters out of line in the usual shower arrangement, except that in this case the curve does not fall so rapidly. From the ground to the maximum the showers observed in this flight increased by a factor of about 50 (Fig. 9).

ABSORPTION OF 13.7 BEV PARTICLES

In Fig. 10 is shown the difference curve obtained by subtracting the Agra vertical coincidence data from the Peshawar data. This curve gives the absorption of the primary particles lying in the energy range from 12.5 to 15 Bev. The average energy of these particles will be approximately 13.7 Bev. The general character of the curve is in good agreement with others of this type obtained both theoretically and experimentally. It exhibits the well-known departure from theory at depths below about 3 meters, and is accordingly further evidence for the production of mesotrons in the atmosphere. The depth of the maximum of the curve, 1.6 meters, is somewhat larger than that predicted from theory.[7] Extra-

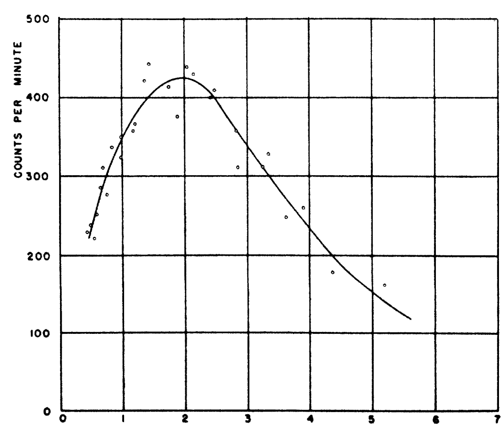

FIG. 8. A quadruple coincidence flight made at Agra.

[7] R. Serber, Phys. Rev. **54**, 317 (1938).

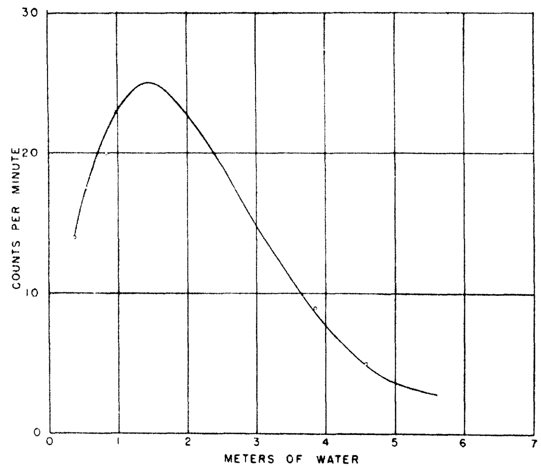

FIG. 9. A flight showing the increase of air showers at the magnetic equator. At the ground, altitude 3000 feet, the rate was 0.5 per minute.

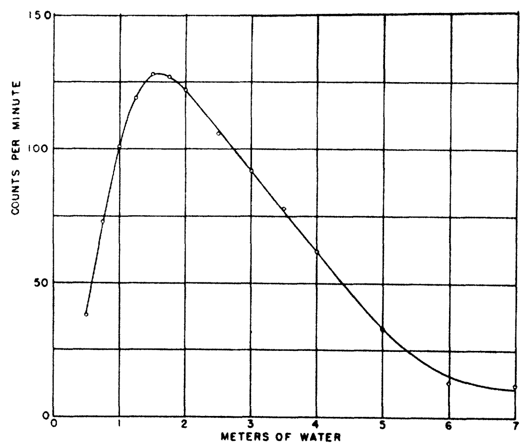

FIG. 10. The difference curve for vertical double coincidences. Peshawar minus Agra-Bangalore average. This curve gives the absorption of the incoming charged particles which have an energy of about 13.7 Bev.

polating the curve to zero depth gives a value which approximately checks the theoretical decrease from the maximum. It is significant to note, however, that the increase in the first half meter below the top of the atmosphere is much more rapid than can be accounted for by the usual shower theory.

CONCLUSION

The results of these flights may be summarized as follows:

(1) The vertical coincidence technique with Geiger counters gives a satisfactory picture of the behavior of the vertically incident radiation, without the necessity of correcting for the effect of showers.

(2) The latitude effects measured with this technique may be significantly different from those obtained with electroscopes or single Geiger counters.

(3) For the determination of the primary energy distribution from the latitude effect, the vertical coincidence data are more significant than the electroscope or single counter data.

(4) The identity of the coincidence curves at Bangalore and at Agra 14° farther north, is direct evidence that the primary radiation spectrum shows a banded structure with little or no energy lying in the range from 15 to 17 Bev.

In conclusion the authors wish to express their appreciation for the invaluable aid rendered by R. A. Millikan in the planning of these experiments, the observations in the field, and the discussion of the results. They sincerely thank the Carnegie Corporation of New York for the financial assistance which made this expedition possible, and they remember with great pleasure their many friends in the Indian Meteorological Service without whose help it would have been impossible to have made so many successful flights.